# ACCRETION OF THE EARLIEST INNER SOLAR SYSTEM PLANETESIMALS BEYOND THE WATER SNOWLINE.

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**Introduction:** Chronological constraints on meteorites, particularly magmatic iron meteorites (sampling the metallic cores of the first generation of planetesimals), suggest that planetesimals began forming almost at the onset of solar system formation [1]. Planetesimal formation is expected at locations of the disk where pebbles pile up to sufficient density to collapse under their collective gravity. Pebbles are likely to pile up more efficiently in specific regions of the disk – the so-called snowlines – associated with the condensation/sublimation fronts of silicates and water [2]–[5]. Although there is a growing consensus that planetesimals associated with carbonaceous (CC) reservoir formed at or beyond the water-snowline, the formation zone of the first generation of non-carbonaceous (NC) planetesimals is poorly understood. Understanding the formation of the first NC planetesimals is of utmost importance because Earth and other terrestrial planets chiefly grew from such planetesimals [6].

Two competing models have been proposed to explain the formation of the first NC planetesimals. The first is that the formation of NC planetesimals was triggered at the water-snowline during an early phase as the water snowline migrated out during disk infall (Class I stage), whereas CC planetesimals formed later at the water-snowline as it migrated back in during subsequent evolution of the disk (Class II stage) [2], [3]. The alternative view is that NC and CC planetesimals formed contemporaneously at the silicate condensation line and water snowline, respectively [4], [5]. Formation of NC iron meteorite parent bodies (IMPBs) at the silicate condensation line should have resulted in their accreting water-free materials, whereas CC IMPBs forming at the water-snowline should have accreted water-rich materials. However, whether the differences in chemical characteristics, especially oxidation states, of NC and CC IMPBs are truly consistent with their accretion at the silicate condensation line and water snowline, respectively, remains elusive because their oxidation states and associated water contents have not been constrained quantitatively.

**Methods:** Here we calculate the oxygen fugacity ($fO_2$) of core-mantle differentiation in magmatic NC and CC IMPBs to constrain the oxidation states of the first generation of planetesimals in each reservoir. At the relatively low pressure and temperatures applicable for core-mantle differentiation in IMPBs, elemental exchange between the metallic cores and silicate mantles is controlled by the $fO_2$ of metal-silicate equilibration ($M_{(metal)} + n/2\ O_{2(g)} = MO_{n/2(silicate)}$) [7]. The oxidation states of bulk planetesimals during core-mantle differentiation can be constrained through the relative depletion of elements in the parent cores that possess similar volatilities but varying degrees of siderophile (metal-loving) character [7]. Fe, Co, and Ni have similar volatilities and hence do not fractionate during condensation/evaporation processes. In contrast, Fe (major element in the cores) can be fractionated relative to Co and Ni at $fO_2$ relevant for core-mantle differentiation because of its less siderophile character. The depletion of Fe relative to Ni and Co in the cores can directly constrain the amount of oxidized Fe in the mantles and, as a result, the $fO_2$ of the bulk planetesimals relative to the iron-wüstite (IW) buffer. The mass balance of Fe between mantles and cores in tandem with those of Ni and Co (assuming all Ni and Co partition into the cores) can be used to quantify the Fe contents of the mantles of IMPBs by using the equation:

$$C_{\mathrm{Fe}}^{\mathrm{mantle}} = \left[\left(\frac{\mathrm{Fe}}{\mathrm{Ni\ or\ Co}}\right)^{\mathrm{bulk}} \times C_{\mathrm{Ni\ or\ Co}}^{\mathrm{core}} - C_{\mathrm{Fe}}^{\mathrm{core}}\right] \times r$$

(Eq. 1)

where $C$ is the concentration of an element in a reservoir and $r$ is the core/mantle mass ratio.

**Results:** The FeO contents of the mantles (assuming all oxidized Fe is FeO) of NC IMPBs computed from Fe/Ni lie in the range 3-16 wt% and those based on Fe/Co are 4-19 wt%. Likewise, the FeO contents of the mantles of CC IMPBs computed from Fe/Ni are 10-25 wt% and those based on Fe/Co are 6-33 wt%. The range of $fO_2$ of metal-silicate equilibration in NC IMPBs implied by Fe/Ni is IW−3.2 to IW−1.7, while Fe/Co gives IW−2.8 to IW−1.5 (Fig.1). By contrast, the range of $fO_2$ of metal-silicate equilibration in CC IMPBs based on Fe/Ni is IW−2.2 to IW−1.2 and based on Fe/Co it is IW−2.6 to IW−1.1. Although CC IMPBs are modestly more oxidized than NC IMPBs, the $fO_2$ of groups IIIF and IVB overlap with their NC counterparts. Combined, the major conclusion of this exercise is that there are only modest differences between the $fO_2$ prevailing during core-mantle differentiation in NC and CC IMPBs.

**Discussion:** Our estimates for $fO_2$ of magmatic NC IMPBs are comparable to the $fO_2$ of non-magmatic NC iron groups determined by mineral equilibria between the co-existing metals and silicates. The $fO_2$ of several other primitive and asteroidal NC achondrites are also comparable to our constraints for NC IMPBs. For example, HEDs yield IW–2.2; angrites IW–1.4; acapulcoites IW–2.0; winonaites IW–2.7; brachinites IW–0.6 to IW+0.4; pallasites-MG IW–1.1 to IW+0.9; lodranites IW–3.1 to IW–0.9; ureilites IW–2.4; and mesosiderites IW–0.5 to IW+0.5 (Fig.1). These values are also comparable to the estimated $fO_2$ of ordinary chondrites (between IW–2.2 and IW–1.5) whereas Rumuruti chondrites record an even more oxidized alteration environment (IW to IW+2). The similarity of the oxidation states of NC IMPBs with almost all meteorites from the NC reservoir (except enstatite chondrites and aubrites), covering a wide range of accretion ages (~0.1-4 Myr after CAIs) suggests that the formation of oxidized NC planetesimals was the norm rather than the exception.

The first formation of substantial FeO has been linked to environments where the $H_2O/H_2$ ratio was much greater (~$10^{-1}$) than that of nebular gas (~$10^{-4}$) [8], [9]. Heating of dust in the protosolar nebula with locally enhanced dust/gas ratios is a viable pathway to producing silicates with substantial FeO contents only if the precursor dust was water-bearing – for example, a mixture of solar condensate dust and ice or structurally bound water in phyllosilicates [8], [9]. An arguably simpler setting is the interaction of aqueous fluids, generated by the melting of ice during $^{26}$Al decay, with metallic Fe within planetesimals that grew from ice-bearing materials [8], [9]. This interaction can form substantial amounts of FeO by the well-characterized reaction: $Fe_{(s)} + H_2O_{(l)} = FeO_{(s)} + H_{2(g)}$ [8]. The high porosity and permeability of planetesimals prior to high-temperature sintering allows for the efficient escape of $H_2$ and the ensuing oxidation of the bulk planetesimals [10]. This scenario has also been suggested to explain the production of FeO-bearing chondrule precursors where liquid water interacted with metallic Fe and magnesium silicates at elevated temperatures within planetesimals [8], [9].

The oxidation states of NC IMPBs, therefore, most likely record a water enriched formation environment via the accretion of either ice or phyllosilicates. Different solar system scenarios can potentially generate such environments. These include: (a) Formation of NC IMPBs at the water-snowline as it moved inwards, followed by the rapid formation of Jupiter's core [1] beyond the water-snowline separating the NC and CC reservoirs. (b) The presence of a dynamic water-snowline periodically drifting in and out in the solar protoplanetary disk due to variations in the infall accretion rate onto the sun [11], [12]. The transient passage of the water-snowline through the inner part of the disk could have triggered the formation of ice-rich NC IMPBs.

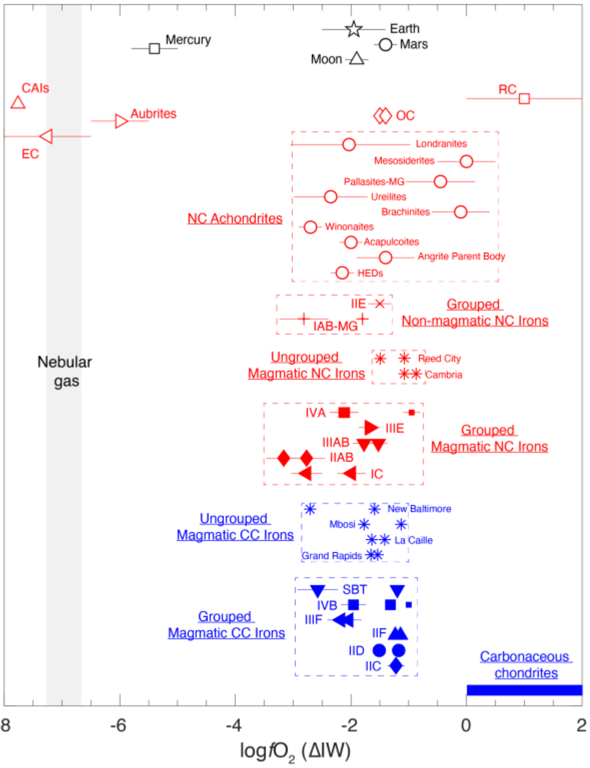

**Fig. 3:** Variations in the oxidation states of various solar system objects and reservoirs.

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